CRITICAL ORIFICE THEORY, DESIGN AND IMPLEMENTATION

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If flow through an orifice's minimum area is maintained at Mach 1, the volume flow rate is only a function of the temperature and the pressure upstream of the orifice. Such a "critical orifice" is useful in air sampling when ambient conditions do not change rapidly. Under those conditions, a critical orifice will passively keep the volume flow rate constant at a known value. This can eliminate measuring sampler flow rates in the field during field tests. This paper presents substantiating laboratory and field test data and makes recommendations for the use of critical orifices in vacuum driven sampling lines.

INTRODUCTION

Critical orifices have been used on sampling lines in DTRA collateral effects field tests for many years. On a typical field test several hundred samplers are deployed at ranges from tens of meters to several miles. The sampling set-up normally consists of a portable generator, a vacuum pump, the orifice and a filter holder. On many of the tests the filter holders were "Wagner" samplers supplied by the Life Sciences Division of Dugway Proving Ground (DPG). Flow rate control was provided through critical orifices, also from DPG.

On a recent test some flow rate measurements through samplers in the field disagreed with some of the assumptions about flow rates through a critical orifice and Wagner sampler combination. This study was initiated to resolve the disagreement.

The study consisted of a review of orifice theory followed by a series of experiments conducted by the authors at the U.S. Army Engineer Research and Development Center (ERDC), Waterways Experiment Station, Vicksburg, MS. The experiments used critical orifices designed according to the theory and manufactured by ERDC, as well as, critical orifices and Wagner samplers from DPG inventory. Results are presented herein.

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THEORY

For the purposes of this paper, a critical orifice is a duct with a minimum area operating with air flowing through that minimum area at Mach one. For this condition the maximum mass flow rate in air (γ=1.4, R=53.3 ft lbf/lbm°) is

$$\omega_{\max} = 0.532 A^* p_0 / \sqrt{T_0} \quad (1)$$

[1]

In equation 1, ω is in lbm/sec, A* is in ft^2, T_0 is in °R, p_0 is in lbf/ft^2 and p_0 and T_0 are total pressure and temperature (stagnation conditions) at the duct inlet. Noting that volume flow is simply mass flow divided by the fluid density, ρ, the volume flow can be expressed as q (ft^3/sec) = ω (lbm/sec)/ρ(lbm/ft^3).

Since air under ambient conditions is a perfect gas, ρ = p/RT and therefore

$$q = 0.532 R (p_0 / p)(T / T_0) A^* \sqrt{T_0}\ . \quad (2)$$

Equation 2 is the volume flow rate (ft^3/sec) through any cross section of the duct. Note that because pressure and temperature change throughout the duct, the volume flow rate is not the same at every cross-section. Mass flow rate is constant throughout. Volume flow rate is not. In using a critical orifice for sampling operations one wants to know the volume flow rate into the inlet of the orifice, not at the throat.

We can simplify equation 2 further when the flow velocity at the orifice inlet is slow. A typical sampling tube ID is 0.375" and desired flow rates are of the order of 1 ft^3/min. At standard conditions (p=14.7 psia, T=70°F) sonic velocity is 1128 ft/sec. Flow velocity using these values is 21.7 ft/sec or Mach = 0.02 which is very slow flow ... essentially isentropic and incompressible in the tube. From the isentropic gas tables, the (p_0/p)(T/T_0) product is equal to 1 for this flow and only 1.02 for velocities 10 times as great. Thus, for flows of interest in sampling lines, equation 2 becomes

$$q = 28.4 A^* \sqrt{T_0}\ . \quad (3)$$

Equation 3 states that, when operating at critical conditions, the volume flow rate is constant for an existing orifice (A* is fixed), unless the ambient temperature changes significantly. (Note: Over the temperature range of 40°F to 100°F the change in q from standard conditions is +/- 3%)

ORIFICE DESIGN

Ducts with minimum areas have many applications. Rocket nozzles, aircraft engine inlets and wind tunnels are some obvious examples where extensive studies and experiments have produced sophisticated designs that operate with high efficiency in difficult environments. Orifices for use in low speed flow sampling lines at near atmospheric pressures can be much simpler. See Figure 1. For this study critical orifices were made from rods approximately 3/8 inch in diameter cut to approximately 2-inch lengths. The outside diameter and length are not critical dimensions. The inlet is a 45-degree countersink. The outlet is a 5/32-inch standard drill hole on centerline. A land separates the countersink and drill hole. The orifice is a drill hole along centerline through the land made with a standard drill bit connecting the apex of the inlet countersink and the apex of the outlet 5/32 drill hole. The tip angle of the 5/32-drill bit is not critical.

Figure 1. Critical orifice schematic

Eighty-six orifices were used in this study. See Figure 2. Sixty-six were machined at ERDC and twenty were from existing DPG inventory. Standard drill size, land length and number identified the ERDC orifices. Example: 55-8-1 used a number 55 drill bit, had a 1/8 inch land, and was number 1 of six identical orifices. The orifices from DPG inventory were numbered 1 through 20. In addition, some ¾ inch rod sections were drilled completely through. Such "orifices" were all land and were designated as 55-1 through 6.

Figure 2. Test orifices.

Equation (3) was used to design all the ERDC orifices, but since standard drill bits have standard diameters, the designed flow-rate is determined by the A* the drill bit produces, rather than A* being determined by one's preferred flow-rate. TABLE 1 shows the flow rates in cubic feet per minute (cfm) and liters per minute (lpm) for critical orifices produced using standard drills. 0ne cfm is equal to 28.3 lpm. Note that drills 50 and 51 bracket the 1 cfm flow rate illustrating the inability to select any specific flow rate. A further complication is the discharge coefficient that causes the actual flow rate to be less than theoretical. So the actual critical flow rate for a critical orifice must be measured. Once the actual value is measured, the orifice will flow at that rate as long as the pressure drop across the orifice is sufficient to maintain critical operation.

TABLE 1. Standard drill critical orifices.

Drill #	Dia"	A*sq"	cfm	lpm
40	0.0980	0.00754	2.055	58.1
41	0.0960	0.00724	1.972	55.8
42	0.0935	0.00687	1.870	52.9
43	0.0890	0.00622	1.695	48.0
44	0.0860	0.00581	1.582	44.8
45	0.0820	0.00528	1.439	40.7
46	0.0810	0.00515	1.404	39.7
47	0.0785	0.00484	1.318	37.3
48	0.0760	0.00454	1.236	35.0
49	0.0730	0.00419	1.140	32.3
50	0.0700	0.00385	1.048	29.7
51	0.0670	0.00353	0.960	27.2
52	0.0635	0.00317	0.863	24.4
53	0.0595	0.00278	0.757	21.4
54	0.0550	0.00238	0.647	18.3
55	0.0520	0.00212	0.579	16.4
56	0.0465	0.00170	0.463	13.1
57	0.0430	0.00145	0.396	11.2
58	0.0420	0.00139	0.377	10.7

All eighty-six orifices used in this study were tested for flow-rate at critical conditions and matched pairs were selected for use in further tests. The selected pairs and their performance are shown in TABLE 2.

Note that the actual flow rate as a percent of the designed flow rate, the “discharge coefficient,” is relatively low compared to the values normally seen for inlets and nozzles. These values could be improved with more sophisticated designs and manufacturing processes. However, there are trade-offs to be made among discharge coefficient, ease of manufacture, and the variance in flow rates of individual orifices in a group of identically produced orifices. When deploying a large number of identical sampling lines, consistent flow rates among the orifices are more important than high discharge coefficients. If higher flow rates are needed, larger diameter orifices can be used to compensate for low discharge coefficients.

TABLE 2. Selected critical orifice pairs.

Source of Orifice	Orifice Identifing Number	Orifice Design Flow Rate liters/min	land length (inches)	Meter flow rate liters/min	Actual flow as % a of designed flow
ERDC	50-16-2	29.7	1/16	27.37	92.2%
ERDC	50-16-6	29.7	1/16	27.29	91.9%
ERDC	55-8-1	16.4	1/8	14.17	86.4%
ERDC	55-8-6	16.4	1/8	14.19	86.5%
ERDC	55-4	16.4	full	13.34	81.3%
ERDC	55-6	16.4	full	13.34	81.3%
ERDC	60-8-1	9.7	1/8	7.97	82.2%
ERDC	60-8-6	9.7	1/8	8.03	82.8%
ERDC	70-8-4	4.7	1/8	3.23	68.7%
ERDC	70-8-5	4.7	1/8	3.21	68.3%
DPG	14	unknown	unknown	30.22	NA
DPG	20	unknown	unknown	30.38	NA

CONFIRMATION OF ORIFICE THEORY

In a typical sampling line the air entering the line must exit the line. Therefore, following the theory described above and illustrated in Figure 3, the ratio of the flow rates at any two points in the line is the inverse of the pressure ratio at those two points.

Data showing a comparison of these ratios for various pressure drops across samplers and for various orifices and flow rates are shown in TABLE 3. The data confirm the theory.

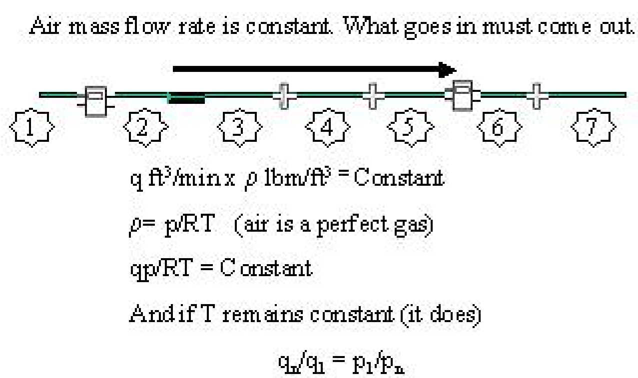


Figure 3. Conservation of mass.

TABLE 3. Conservation of mass data

Conservation of Mass Confirmed - $q_{inlet} \times p_{ambient} = p_{orifice\ inlet} \times q_{orifice}$										
Date: 08/06/04										
Setup as shown. Flow is left to right.										
							Pump			
Ambient Pressure psia ($p_{ambient}$)	Meter l/min (q_{inlet})	Pressure psig (p_2)	Sampler Number	Pressure psig ($p_{orifice\ inlet}$)	Meter l/min ($q_{orifice}$)	Orifice number		$q_{inlet}/q_{orifice}$	$p_{orifice\ inlet}/p_{ambient}$	% difference
14.64	19.3	14.54	W	9.24	30.7	20		0.629	0.631	-0.39%
14.64	24.1	14.54	V5	11.48	30.9	20		0.780	0.784	-0.54%
14.64	20.65	14.57	V9	9.97	30.9	20		0.668	0.681	-1.87%
14.64	16.4	14.54	V15	8.04	29.8	20		0.550	0.549	0.21%
14.65	12.78	14.62	V5	13.17	14.28	55-8-1		0.895	0.899	-0.45%
14.65	11.73	14.59	V9	12.18	14.34	55-8-1		0.818	0.831	-1.61%
14.65	10.52	14.58	V15	10.99	14.34	55-8-1		0.734	0.750	-2.21%
14.65	7.54	14.61	V5	13.8	8	60-8-1		0.943	0.942	0.06%
14.65	7.16	14.61	V10	13.15	8	60-8-1		0.895	0.898	-0.29%
14.65	6.56	14.61	V15	12.3	8.02	60-8-1		0.818	0.840	-2.58%
14.65	6.15	14.61	V20	11.79	8.02	60-8-1		0.767	0.805	-4.71%

TEST SETUP – FLOW RATE MEASUREMENTS

Flow rates were measured using the DryCal DC-Lite Model H flow meter. The meter measures flow rate in actual liters per minute to an accuracy of +/- 1% over the range of 0.5 to 30 lpm. It is designed to operate at near ambient inlet pressures. The measured pressure drop across the meter over that range is shown in Figure 4. Based on this data, the effect of the meter on flow rate is considered negligible for this study.

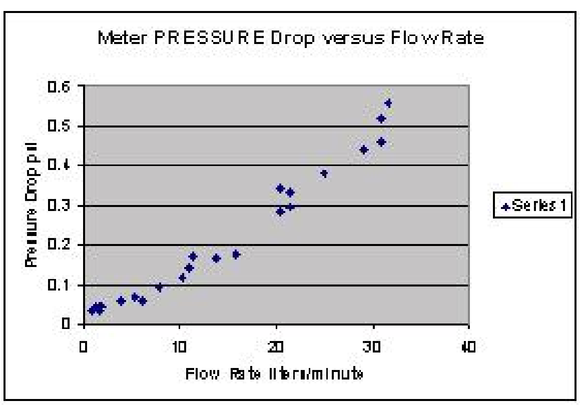


Figure 4. DryCal DC-Lite model H - Pressure drop versus flow rate.

TEST SETUP – SAMPLERS

Two types of samplers were used in this study. See Figure 5. The Wagner sampler has been in use by the Life Sciences Division, Dugway Proving Ground (DPG) for many years. It has a two-piece aluminum body, containing a supporting screen and 25mm diameter filter paper. The second sampler was Gelman Sciences product #1119, a plastic filter holder containing a 47mm diameter filter paper and supporting screen. Each sampler was used to investigate the effect on flow rate through the sampling line with the sampler upstream and downstream of the critical orifice. The Gelman was also used to systematically increase the pressure drop in the sampling line and across the sampler by inserting multiple filter papers. Several Wagner samplers were used to investigate the variation in pressure drop and flow rates caused by different samplers. Wagner samplers were also used to test multiple sampling lines on a single vacuum pump and to investigate the effect of a critical orifice on the viability of Bacillus thuringiensis (BT) spores when the orifice was placed upstream of the sampler in the sampling line.

Figure 5. Gelman and Wagner samplers.

TEST SETUP – SAMPLING LINE TEST ELEMENTS

A typical sampling line goes from inlet to sampler to orifice to vacuum pump. The theory described above suggests that a better arrangement would be orifice to sampler to pump. In this study all configurations were investigated using the elements shown in Figure 6.

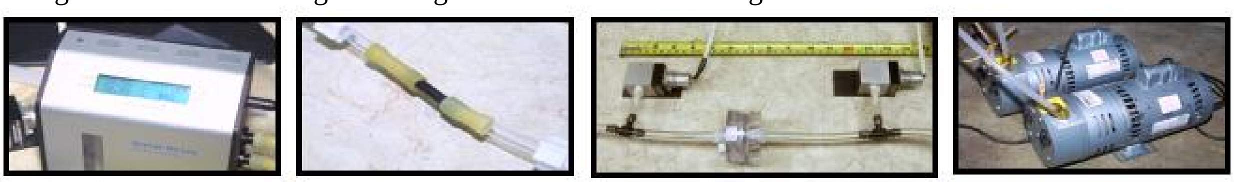


Figure 6. Test elements: meter - orifice - sampler and pressure transducer - vacuum pump.

TEST RESULT - PRESSURE DROP VERSUS FLOW RATE FOR WAGNER SAMPLERS

The flow rate through each of four Wagner samplers was varied and the pressure drop across the sampler was measured. The test set up was inlet to meter to sampler to valve to vacuum pump. Results are shown in Figure 7. The pressure drop for a Wagner sampler flowing one cfm of ambient air is about 9 psi. At ½ cfm it is 3.5 psi.

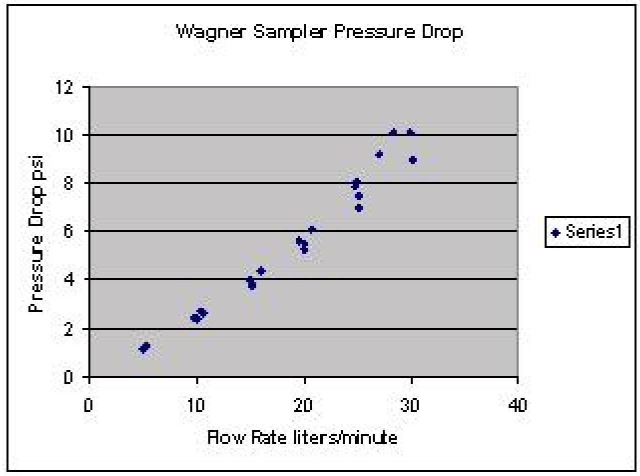


Figure 7. Pressure drop for 4 Wagner samplers.

TEST RESULT – THE EFFECT OF SAMPLER PRESSURE DROP ON AMBIENT AIR FLOW RATE WITH SAMPLER FIRST.

The effect of the pressure drop across the sampler on the flow rate through a sampling line was evaluated by systematically increasing the flow resistance of the sampler by adding additional filter disks to a Gelman sampler. This same effect can occur during operation in dense particulate clouds when sampled material collects on the filter. The test setup was inlet to meter to sampler to orifice to vacuum pump. Results are shown in Figure 8. Notice the substantial change in flow rate, even though the orifice is operating critical.

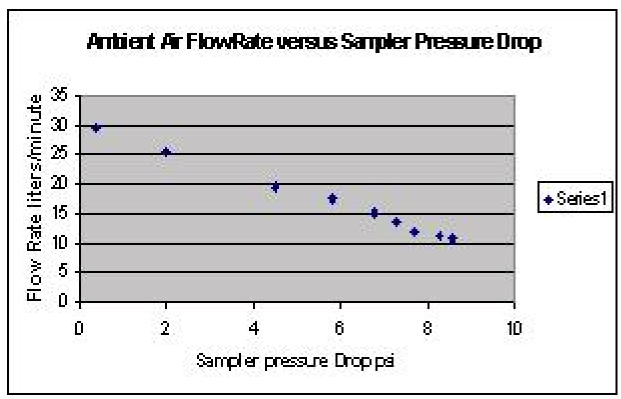


Figure 8. Flow rate with increasing sampler resistance - sampler upstream of orifice.

TEST RESULT – THE EFFECT OF SAMPLER PRESSURE DROP ON AMBIENT AIR FLOW RATE WITH ORIFICE FIRST.

The effect of the pressure drop across the sampler on the flow rate through a sampling line was evaluated by systematically increasing the flow resistance of the sampler by adding additional filter disks to a Gelman sampler. The test setup was inlet to meter to orifice to sampler to vacuum pump. Results are shown in Figure 9. The results are for two orifices with different flow rates. Notice that the flow rates remain essentially constant at the critical flow rate until the downstream pressure drop becomes too high for the orifice to stay critical. Up to this point, an orifice-first deployment will keep a constant flow rate through the sampler even though material collects on the filter.

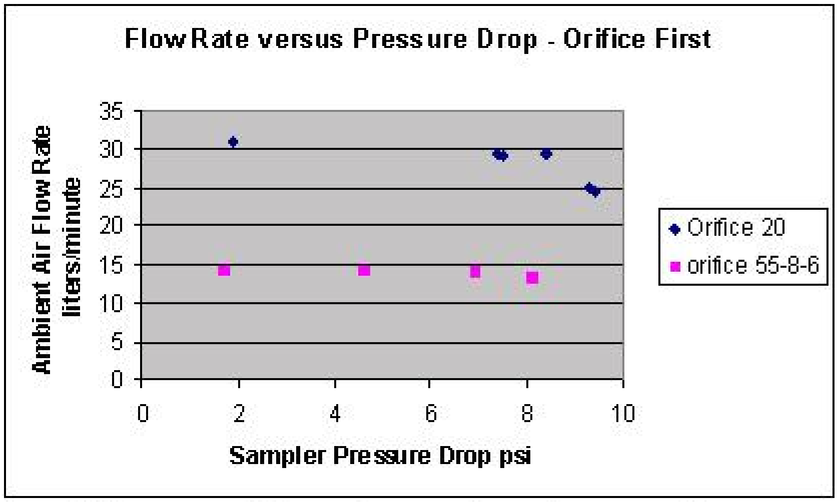


Figure 9. Flow rate with increasing sampler resistance - orifice upstream of sampler.

TEST RESULT – FOR BEST FLOW CONTROL THE ORIFICE SHOULD BE PLACED UPSTREAM OF THE SAMPLER.

TABLE 4. Flow rate control is more effective with orifice upstream of sampler.

Flow Rate - Wagner Samplers and Orifice									
Date: 08/06/04									
Setup as shown. Flow is left to right.									
			Pump						Pump
Meter l/min	Sampler Number	Orifice number		% of Critical Flow Rate		Meter l/min	Orifice number	Sampler Number	% of Critical Flow Rate
30.89	none	20		100.0%		31.12	20	none	100.0%
19.45	A	20		63.0%		24.55	20	A	78.9%
18.86	B	20		61.1%		24.09	20	B	77.4%
15.33	C	20		49.6%		23.87	20	C	76.7%
20.2	D	20		65.4%		24.67	20	D	79.3%
14.31	none	55-8-1		100.0%		14.21	55-8-1	none	100.0%
11.11	A	55-8-1		77.6%		14.17	55-8-1	A	99.7%
10.2	B	55-8-1		71.3%		14.13	55-8-1	B	99.4%
4.6	C	55-8-1	Suspect	32.1%		13.95	55-8-1	C	98.2%
11.59	D	55-8-1		81.0%		14.21	55-8-1	D	100.0%

Ambient air flow rates through four Wagner samplers were evaluated using two different orifices. Results are shown in TABLE 4. On the left the setup is sampler first. On the right the orifice is first. Note the wide variation in flow rates with the sampler first. With the orifice first the flow rates are much more uniform, even when the orifice is not critical (the pressure drop across the samplers at the high flow rate prevents orifice 20 from being critical). At lower flow rate (55-8-1), the pressure drop through the downstream sampler permits the upstream orifice to remain critical and the flow stays critical through the sampling line in spite of variations in sampler resistance.

TEST RESULT – CORRECTION TO TEST DATA PREVIOUSLY ACQUIRED USING WAGNER SAMPLERS

In several previous test series data has been acquired using sampler lines with Wagner samplers deployed upstream of DPG critical orifices. In some of those cases in-field flow rates have not been measured and the sampling flow rate has been assumed to be the design flow rate of the critical orifice. For those cases the data should be corrected to reflect the actual flow rate.

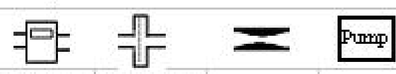
To determine what that correction should be, 20 Wagner samplers that were sterilized and ready for deployment were tested upstream of a DPG critical orifice. The flow rates were measured and compared with the design flow rate and the actual flow rate for the critical orifice. The data and suggested correction factors are presented in TABLE 5. Since the actual flow rates were substantially less than the assumed flow rates, densities determined using assumed flow rates should be increased by factors of 1/0.629 = 1.59 or 1/0.674 = 1.48 as appropriate.

TABLE 5. Correction to previously acquired data.

Correction to Ambient Flow Rate Through Sampler

Setup as shown. Flow is left to right. Ambient pressure is 14.7 psia.

Samplers are Wagner Samplers. Orifice is DPG 20



Sampler Number	Meter 27 l/min	Sampler Number	Meter 27 l/min		
1	18.93	11	19.1		
2	15.01	12	20.2		
3	11.15	25	19.3		DPG 20 critical flow is 30.38 liters/minute
4	16.98	26	20.2		Average flow through 20 wagners is 19.1 liters /minute
5	19.83	27	19.4		Ratio 19.1/30.38 = 0.629
6	19.21	28	18.8		If one assumed the DPG orifice was 1cfm (28.3 lpm)
7	19.6	29	19.5		Ratio 19.1/28.3 = 0.674
8	19.8	30	19.1		
9	28.7	31	17.7		
10	19	32	20.2		

TEST RESULT – FLOWS WITH MULTIPLE SAMPLING LINES PER PUMP

In previous field tests multiple sampling lines have frequently been used on a single vacuum pump. The effect on flow rate with two or three sampling lines per pump using Wagner samplers was investigated and the results are shown in Figures 10 through 12.

Ambient Pressure psia	Meter 28 l/min	Sampler Number	Orifice number 14		Flow Ratio (act/crit)
14.6	19.37	A	30.22	Pump	64.1%
14.6	19.72	D	30.38		64.9%
Ambient Pressure psia	Meter 29 l/min	Sampler Number	Orifice number 20		

Ambient Pressure psia	Meter 30 l/min	Sampler Number	Orifice number 70-8-5		Flow Ratio (act/crit)
14.7	1.69	7	3.21	Pump	52.6%
14.7	1.99	8	3.33		59.8%
Ambient Pressure psia	Meter 27 l/min	Sampler Number	Orifice number 70-8-4		

Ambient Pressure psia	Meter 30 l/min	Sampler Number	Orifice number 14		Flow Ratio (act/crit)
14.7	15.3	7	30.22	Pump	50.6%
14.7	16.2	8	30.38		53.3%
Ambient Pressure psia	Meter 27 l/min	Sampler Number	Orifice number 20		

Note: orifice first

Ambient Pressure psia	Meter 28 l/min	Orifice Number 14	Sampler number		Flow Ratio (act/crit)
14.6	22.04	30.22	A	Pump	72.9%
14.6	22.37	30.38	D		73.6%
Ambient Pressure psia	Meter 29 l/min	Orifice Number 20	Sampler number		

Figure 10. Flows with two sampling lines per pump.

Sampler First - 0.5 cfm Orifice

Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-1		Flow Ratio (act/crit)
14.6	11.01	A	14.17		77.7%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-5	Pump	Flow Ratio (act/crit)
14.6	11.31	D	14.14		80.0%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-6		Flow Ratio (act/crit)
14.6	10.43	B	14.19		73.5%

Sampler First – 1 cfm Orifice

Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 7		Flow Ratio (act/crit)
14.6	18.55	A	30.55		60.7%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 20	Pump	Flow Ratio (act/crit)
14.6	18.49	D	30.38		60.9%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 14		Flow Ratio (act/crit)
14.6	17.42	B	30.22		57.6%

Figure 11. Flows with three sampling lines per pump.

Sampler First – 0.5 cfm Orifice

Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-1		Flow Ratio (act/crit)
14.6	11.01	A	14.17		77.7%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-5	Pump	Flow Ratio (act/crit)
14.6	11.31	D	14.14		80.0%
Ambient Pressure psia	Meter l/min	Sampler Number	Orifice number 55-8-6		Flow Ratio (act/crit)
14.6	10.43	B	14.19		73.5%

Orifice First – 0.5 cfm Orifice

Ambient Pressure psia	Meter l/min	Orifice Number 55-8-1	Sampler number		Flow Ratio (act/crit)
14.6	14.14	14.17	A		99.8%
Ambient Pressure psia	Meter l/min	Orifice Number 55-8-5	Sampler number	Pump	
14.6	14.09	14.14	D		99.6%
Ambient Pressure psia	Meter l/min	Orifice Number 55-8-6	Sampler number		
14.6	14.18	14.19	B		99.9%

Figure 12. Flows with three sampling lines per pump.

A study of the above data shows that, for the pumps and lines currently employed, a single pump cannot support multiple sampling lines at a one cfm sampling rate. A single pump can support up to three sampling lines at the critical orifice flow rate if the flow rate is ½ cfm and the orifices are upstream of the sampler.

TEST RESULT – THERE IS NO EFFECT ON THE VIABILITY OF BT SPORES PASSING THROUGH A CRITICAL ORIFICE

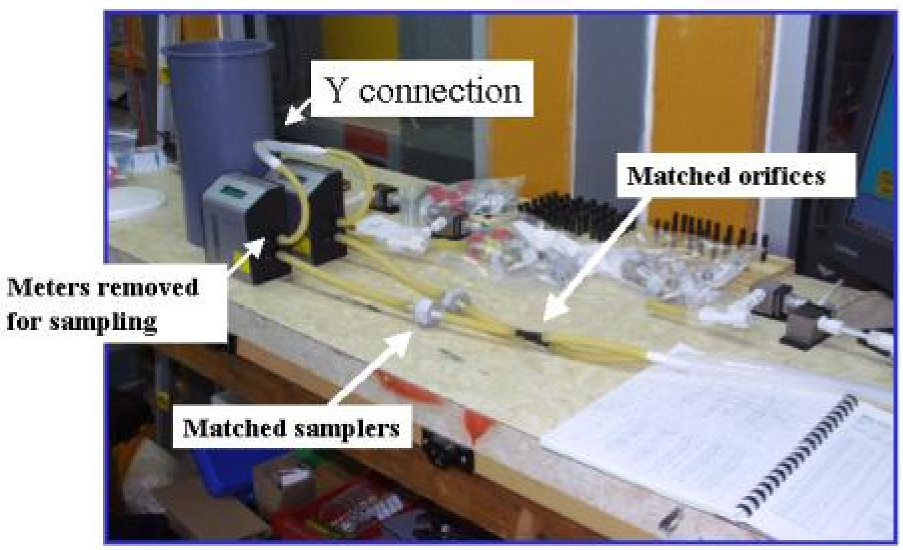


Figure 13. Viability test apparatus.

Standard practice is to field sampling lines with samplers upstream of critical orifices. One rationale often expressed for so doing is that passage through a critical orifice will damage spores. To test this theory we examined the viability of BT spores prior to and subsequent to passage through sampling lines with the orifice upstream and with the orifice down stream. The technique employed used a simulant mixture of BT spores and Indium oxide. The viability is unchanged if the ratio of spores (CFUs) to Indium atoms remains constant throughout the process. The test setup is shown in Figure 13. It is designed to acquire two identical samples and has two identical sampling lines that simultaneously sample from a single input point. One sample for indium analysis. The other is for bio assay. The resultant data, shown in TABLE 6, indicates no discernable effect.

TABLE 6. Viability data.

Effect of Critical Orifice on Bio Viability

Bio Sample ID	cfu	INAA Sample ID	ug In	cfu/ug (individual)	total cfu/ug (all material)
Sampler first (1 cfm orifice)					
WAGNER # 08	4.43E+09	WAGNER #05	503	8.81E+06	**1.44E+07**
WAGNER # 27	1.75E+07	WAGNER #29	118	1.48E+05	
WAGNER # 30	6.53E+09	WAGNER #25	280	2.33E+07	
WAGNER # 32	5.18E+09	WAGNER #26	218	2.38E+07	
Orifice first (1 cfm orifice)					
WAGNER # 13	6.08E+08	WAGNER #24	217	2.80E+06	**7.42E+06**
WAGNER # 15	4.93E+08	WAGNER #19	285	1.73E+06	
WAGNER # 17	8.28E+09	WAGNER #18	943	8.78E+06	
WAGNER # 22	4.18E+09	WAGNER #16	384	1.09E+07	
Sampler first (8 l/m orifice)					
WAGNER # 01	1.54E+07	WAGNER #10	21.3	7.21E+05	**1.44E+06**
WAGNER # 11	5.15E+07	WAGNER #23	25	2.06E+06	
Orifice first (8 l/m orifice)					
WAGNER # 14	3.63E+07	WAGNER #28	13.4	2.71E+06	**2.23E+06**
WAGNER # 21	3.85E+07	WAGNER #20	20.2	1.91E+06	
Virgin Material					
5.95E+09 cfu/0.0509 gm of mix				567 ug In/32 gm of mix	**6.60E+06**

TEST RESULT – THE ½ CFM CRITICAL ORIFICE UNLIKELY TO CLOG

Another often expressed rationale for fielding the sampler upstream of the orifice is that such an arrangement prevents the orifice from clogging. To test this theory, two ½ cfm orifices and Wagner sampler lines were fielded during recent tests where plumes of Kaolin powder were explosively lofted for balloon sampler shakedown tests. The orifice/sampler combinations were placed to sample in locations where heavy concentrations of Kaolin were expected. No clogging was observed and the flow rates through the sampling line were critical both pre and post test. A post-test view of the samplers is presented in Figure 14.

Figure 14. Post test orifice and Wagner sampler.

CONCLUSIONS

This study examined the use of critical orifices to control the flow rate in atmospheric sampling lines. The primary application envisioned was sampling respirable particles using filter holders with filter papers at flow rates up to 1 cfm. Issues addressed included the theory of critical orifices, the position of the orifice in the sampling line, multiple sampling lines on a single vacuum pump, the effect of the orifice on BT spores passing through it and debris clogging the orifice. The test results support the following recommendations and conclusions.

1. A simple critical orifice (a duct with a minimum area operating with air flowing through that minimum area at Mach one) can be designed to passively maintain a constant flow rate through a vacuum driven sampling line.
2. A critical orifice has a constant volume flow rate through itself and controls the mass flow rate through the sampling line.
3. If the orifice is the first element in the sampling line, the ambient air flow rate can be maintained constant at the critical value throughout the sampling period in spite of changing resistance through the sampler. This eliminates a need for in-field flow rate measurements.
4. If the sampler is the first element in the sampling line, the ambient air flow rate is significantly less than the critical flow rate through the orifice and decreases further as the resistance across the sampler increases due to accumulation of sampled material on the filter. In-field flow rate measurements and assumptions as to how the flow rate changed with time during the sampling period are required.
5. A critical orifice has no effect on BT spores passing through it.
6. A critical orifice sampling at ½ cfm does not clog in relatively dense dry material clouds.
7. For previous DTRA tests where single Wagner samplers were deployed upstream of DPG samplers the actual flow rates were substantially less than the stated critical orifice flow rates. Since the cloud densities were subsequently determined assuming critical flow rates, cloud densities should be increased by approximately 50%.
8. For future DTRA tests with dry particulate simulants the author recommends that sampling lines be deployed with ½ cfm critical orifices as the first element in a sampling line. Under normal test conditions, a single pump can support three sampling lines, there will be no clogging of the orifices and no adverse effect on the simulant. If non-spore forms of bio simulant or liquid simulants are used, additional considerations must be addressed. In all cases with the orifice first, recommend each sampler/orifice combination be securely isolated and preserved in the field and transported in tact to the lab for analysis.

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